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OPTIMAL CODING OF OBJECTS WHEN CLASSIFYING THEM BY METHODS OF PATTERN RECOGNITION

by

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(Perm')

FOREIGN AEROSPACE SCIENCE & TECHNOLOGY CENTER

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А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
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К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
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М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	sinh^{-1}
cos	cos	ch	cosh	arc ch	cosh^{-1}
tg	tan	th	tanh	arc th	tanh^{-1}
ctg	cot	cth	coth	arc cth	coth^{-1}
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

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OPTIMAL CODING OF OBJECTS WHEN CLASSIFYING THEM BY METHODS OF PATTERN RECOGNITION

Yu. V. Devingtal'
(Perm')

Proposed is a method that in some sense is the optimal coding of objects in the classification of complex systems with the help of a dividing plane. The determination of the codes is reduced to the solution of a problem of linear programming. The identification of objects not included in the teaching sequence consists in the summation of codes. The obtained table of codes can be used, for example, for determining the oil content of beds from the data of geophysical measurements.

1. Preliminary observations. The methods of pattern recognition now are widely used not only for the identification of visual forms, but also for the classification of complex systems of different types which are described by a large quantity of parameters or criteria. Criteria are either results of some quantitative measurements or qualitative evaluations. It is possible to assume that each parameter has a finite number of gradations. For the continuously varying parameters their range of change is divided into a finite number of intervals, in each of which the value of the parameter can be considered constant.

To input information about the object into a computer each value of parameter in coded by some method.

If objects are characterized by n parameters, each of which can take k_i ($i=1, 2, ..., n$) values, then for coding an object a table of codes preliminarily is compiled

$$\{x_{ij}\}\ i=1, 2, ..., n; j=1, 2, ..., k_i,$$

where x_{ij} - number by which the jth value of a parameter with the number i is coded. In practice the codes x_{ij} sometimes coincide with the numerical values of the measurements of parameters, sometimes they are some conditional numbers. It is almost always thought that different values of codes must correspond to the different values of parameter. The selection of the table $\{x_{ij}\}$ depends on the conditions of a specific problem and in many respects is determined by convenience in writing the codes into the computer. In studies dedicated to pattern recognition it is usually assumed that this coding has already been carried out, and the objects are considered as points whose coordinates coincide with the values of the codes. This space is called the space of criteria.

The simplest method of classification is the division of objects into two classes A and B with the help of a dividing hyperplane. The different methods of constructing such a hyperplane are described, for example, in [1-4]. However, not always is coding of initial information successful. Sometimes the obtained point sets do not share one hyperplane, which strongly narrows the applicability of this simple method of division.

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Example. Let the objects be characterized by two parameters, each of which can take three different values, and let the table of the codes take the form:

Let us assign the teaching sequence this form: let points (x_{12}, x_{21}), (x_{12}, x_{23}) belong to class A, and points (x_{11}, x_{22}), (x_{13}, x_{22}) - to class B.

With this coding of the values of the parameters these two classes, obviously, cannot be divided by one plane. A similar picture is also encountered in practical problems: sometimes an unsuccessful method of coding does not permit the use of the dividing plane for the classification. Therefore, we naturally have the problem of constructing a method of coding objects such that the teaching sequence in a sense in the best way would be divided by a given hyperplane. In this study one method constructing this table of codes $\{x_{ij}\}$ is examined. In contrast to [1-4], where the points of the teaching sequence are considered to be predetermined), i.e., the table of codes $\{x_{ij}\}$ has been selected previously and the dividing hyperplane is sought, we consider the hyperplane the given, and we will seek the elements of the table of codes $\{x_{ij}\}$. As will be clear below, this method widens the class of sets divided by one hyperplane.

2. Formulation of the problem. Without limiting generality, it is possible to assume that the unknown values of codes x_{ij} satisfy the inequalities

$$0 \leq x_{ij} \leq 1 \quad i=1, 2, ..., n; \; j=1, 2, ..., k_i. \tag{2.1}$$

As the dividing plane let us take the plane

$$x_1 + x_2 + \ldots + x_n - \frac{n}{2} = 0, \tag{2.2}$$

which divides in half an n-dimensional hyper cube.

Since each specific object is characterized by certain values of the parameters, then it suffices to indicate, when specifying an object, what value of each parameter enters into the description of this object, i.e., it suffices to assign the sequence of second indices j_i (i=1, 2, ..., n) in codes x_{ij} of the criteria which define the objects of the teaching sequence. In other words, it is necessary to indicate that for a given object the first parameter in its description a takes value with a number j_1, the second - with a number j_2 and so forth.

Let the teaching sequence be specified by the method described above. Each object is written in the form of a set n of whole numbers j_{ir} (i=1, 2, ..., n), where r - number of the object. Let r=1, 2, ..., m_1 correspond to the objects of class A, and r=m_1+, m_1+2, ..., m_1+m_2 - to objects of class B. Let us denote by $N = \sum_{i=1}^{n} k_i$ the total number of all possible gradations of the parameters; by $\epsilon/\sqrt{n}$ - distance from dividing plane (2.2) to the point of the teaching sequence nearest to it. It is possible to require, for example, that the plane (2.2) divide the teaching sequence so that the distance from the nearest point of the teaching sequence to the dividing plane would be greatest. In this case we will arrive at the following of linear programming: to find values ϵ and x_{ij} (i=1, 2, ..., n; j=1, 2, ..., k_i) such that ϵ takes the greatest value with satisfaction of the conditions

$$x_{1j_{1r}} + x_{2j_{2r}} + \ldots + x_{nj_{nr}} - \varepsilon - \frac{n}{2} \geqslant 0 \tag{2.3}$$

for r=1, 2, ..., m_1;

$$-x_{1j_{1r}} - x_{2j_{2r}} - \ldots - x_{nj_{nr}} - \varepsilon + \frac{n}{2} \geqslant 0 \tag{2.3'}$$

for $r=m_1+1, m_1+2, ..., m_1+m_2$, where $\epsilon \geq 0$ and $0 \leq x_{ij} \leq 1$.

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Conditions (2.3) and (2.3') mean that the points of class A are located on one side of the plane (2.2), and those of class B on other side of this plane. Conditions (2.3) and (2.3') can be written in the form of one system of inequalities

$$- \sum_{i=1}^{n} \sum_{j=1}^{k_i} C_{ij}^{(r)} x_{ij} + \varepsilon \leqslant \delta_r \frac{n}{2}, \quad r = 1, 2, \ldots, m_1 + m_2, \qquad (2.4)$$

where

$$\delta_r = \begin{cases} -1, & r = 1, 2, \ldots, m_1, \\ 1, & r = m_1 + 1,\ m_1 + 2, \ldots, m_1 + m_2, \end{cases}$$

$$C_{ij}^{(r)} = \begin{cases} 1, & j = j_{ir},\ r = 1, 2, \ldots, m_1, \\ -1, & j = j_{ir},\ r = m_1 + 1,\ m_1 + 2, \ldots, m_1 + m_2, \\ 0, & j \neq j_{ir},\ r = 1, 2, \ldots, m_1 + m_2. \end{cases}$$

3. Solubility of the problem and some observations about its solution. The problem of linear programming formulated above is always soluble, since its solution set is not empty, and the linear form is limited [5, page 110, theorem 4.4].

For example,

$$\epsilon=0, \quad x_{ij}=0.5, \quad i=1, 2, ..., n; \quad j=1, 2, ..., k_i \qquad (3.1)$$

is the solution of this problem, and the linear form of ϵ, with the limits used, satisfies the inequality

$$0 \leqslant \varepsilon \leqslant \frac{n}{2}.$$

The solubility of a linear programming problem is not equivalent to solving the problem of dividing objects into two classes with the help of a hyperplane (2.2). If solution of the problem of linear programming will give max $\epsilon=0$, then the of construction a hyperplane which divides the teaching sequence is impossible for any choice of table $\{x_{ij}\}$.

If for a certain coding of objects $\{x_{ij}^*\}$ it is possible to construct the dividing hyperplane

$$a_1x_1^*+a_2x_2^*+...+a_nx_n^*-a_0=0, \qquad (3.2)$$

then there is always a coding $\{x_{ij}^*\}$ for which the teaching sequence is divided by a hyperplane (2.2) with satisfaction of the conditions (2.1).

Actually, since (3.2) is the dividing plane, then the coordinates of the objects of the teaching sequence satisfy the inequalities

$$\sum_{i=1}^{n} a_i x_{ij_r}^* - a_0 > 0 \qquad (3.3)$$

with $r=1, 2, ..., m_1$

and

$$\sum_{i=1}^{n} a_i x_{ij_r}^* - a_0 < 0 \qquad (3.3')$$

with $r=m_1+1, m_1+2, ..., m_1+m_2$.

Let us denote the largest value of the code of values of the parameter with the number i in the training sequence by $x_{i\,\max}^* = \max x_{ij_r}^*$, and the smallest value by $-x_{i\,\min}^* = \min\limits_{r} x_{ij_r}^*$, $r = 1, 2, \ldots, m_1 + m_2$.

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Without limiting generality, it is possible to consider all $a_i>0$ $i=1, 2, ..., n$, since, if some a_k proves to be equal to zero, then the parameter with number k does not participate in recognition, and the object can be described by a smaller number of parameters without sacrificing the division. With some $a_\ell<0$ we can preliminarily change the directions of an axis having the number ℓ, i.e., replace x_ℓ^* by $-x_\ell^*$, in other words, to change the sign in the codes of the parameter having the number ℓ.

In (3.2) let us replace the variables

$$x_i^{\bullet}=c_i x_i+d_i, \qquad (3.4)$$

where

$$c_i=\frac{2}{a_i n}(a_0-nd), \quad d_i=\frac{d}{a_i}$$

$$d\leqslant \min\left[\inf_i(a_i x^{\bullet}_{i\,\min});\ \frac{2}{n}a_0-\sup_i(a_i x^{\bullet}_{i\,\max})\right], \qquad (3.5)$$

$i=1,2,\ldots,n.$

Substituting (3.4) in (3.2), we will obtain

$$\sum_{k=1}^{n} a_k x_k^{\bullet}-a_0=\frac{2}{n}(a_0-nd)\ \sum_{k=1}^{n} x_k+nd-a_0=0$$

or after division by $2(a_0\text{-}nd)/n\neq 0$ we will obtain the equation of a hyperplane with the form (2.2)

$$\sum_{k=1}^{n} x_k-\frac{n}{2}=0.$$

Let us note that $a_0\text{-}nd>0$ because of the selection of d. Actually, if the smallest value in (3.5) is $\inf_i(a_i x^{\bullet}_{i\,\min})$, then $d\leqslant\inf_i(a_i x^{\bullet}_{i\,\min})$ and

$$a_0-nd\geqslant a_0-n\inf_i(a_i x^{\bullet}_{i\,\min})\geqslant a_0-\sum_{i=1}^{n} a_i x^{\bullet}_{i\,\min}\geqslant$$

$$\geqslant a_0-\sum_{i=1}^{n} a_i x^{\bullet}_{ij_r}>0 \quad (m_1+1\leqslant r\leqslant m_1+m_2)$$

because of the relationship (3.3').

In the second case

$$a_0 - nd \geqslant a_0 - 2a_0 + n \sup_i (a_i x^*_{i\,\max}) \geqslant$$

$$\geqslant -a_0 + \sum_{i=1}^{n} a_i x^*_{i\,\max} \geqslant -a_0 + \sum_{i=1}^{n} a_i x^*_{ij_r} > 0 \quad 1 \leqslant r \leqslant m_1$$

because of the relation (3.3).

Satisfaction of the condition (2.1) also easily is checked from the relation (3.4)

$$x_{ij_r} = \frac{(a_i x^*_{ij_r} - d)\, n}{2(a_0 - nd)}.$$

Because of the selection of d $x_{ij_r} \geqslant 0$, since a_0-nd>0 and $a_i x^*_{ij_r} - d \geqslant \inf_i (a_i x^*_{i\,\min}) - d \geqslant 0$.

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Similarly, $x_{ij_r} \leqslant 1$, since $1 - x_{ij_r} = \frac{2a_0 - nd - n a_i x^*_{ij_r}}{2(a_0 - nd)} > \frac{2a_0 - nd - n \sup_i (a_i x^*_{i\,\max})}{2(a_0 - nd)} > 0.$

The conditions (3.3) and (3.3') with this replacement will become the inequalities

$$\sum_{i=1}^{n} x_{ij_r} - \frac{n}{2} > 0$$

with r=1, 2, ..., m_1, while

$$\sum_{i=1}^{n} x_{ij_r} - \frac{n}{2} < 0$$

with r=m_1+1, m_1+2, ..., m_1+m_2, i.e., there is an ϵ>0, such that the conditions (2.1), (2.3), (2.3') are satisfied, and therefore the problem in p. 2 will in this case be solution such that max ϵ>0.

A change in the coding of objects can convert nondividing sets into dividing ones.

Let us return to the example. In this case the problem of linear programming will consist in defining seven unknowns ϵ, x_{11}, x_{12}, x_{13}, x_{21}, x_{22}, x_{23} so as to obtain max ϵ during the limits

$$
\begin{aligned}
x_{12} + x_{21} - \varepsilon - 1 &\geqslant 0, \\
x_{12} + x_{23} - \varepsilon - 1 &\geqslant 0, \\
- x_{11} - x_{22} - \varepsilon + 1 &\geqslant 0, \\
- x_{13} - x_{22} - \varepsilon + 1 &\geqslant 0, \\
0 \leqslant x_{ij} \leqslant 1, \quad i = 1, 2; \quad j &= 1, 2, 3.
\end{aligned}
$$

It is not difficult to verify that the solution to this problem will be the numbers

$$
\begin{gathered}
\varepsilon = 1, \quad x_{11} = 0, \quad x_{12} = 1, \quad x_{13} = 0, \\
x_{21} = 1, \quad x_{22} = 0, \quad x_{23} = 1,
\end{gathered}
$$

and the plane $x_1+x_2-1=0$ will divide the ,eaching sequence indicated.

From the example it is evident that the codes of the different values of the parameters can coincide ($x_{11}=x_{13}, x_{21}=x_{23}$). If some gradation of a parameter is encountered only in class A (or class B), then the corresponding value of the code will be equal to 1 (or respectively to 0). If a certain gradation is not encountered in any of the classes (this sometimes happens in practical problems with insufficient representativeness of the training sequence), then let us assume the value of the corresponding code to be equal to 0.5. It should be stressed that the solubility of the of linear programming problem does not mean that any two sets can be divided by one plane. For example, if one and the same object will be written in the training sequence and in class A and class B, then this will lead to max $\epsilon=0$.

Let us consider conditions under which the solution (3.1) will be optimal, i.e., let us find the criterion of insolubility of the division problem. For this let us switch over to a dual Problem. In it a minimum with the linear form

$$
w = -\sum_{k=1}^{m_1} u_k + \sum_{k=m_1+1}^{m_1+m_2+N} u_k \tag{3.6}
$$

is sought under the conditions

$$\sum_{k=1}^{m_1+m_2} u_k \geqslant 1, \tag{3.7}$$

$$\sum_{r=1}^{m_1+m_2} C_{ij}^{(r)} u_r + u_{m_1+m_2+k_1+k_2+\ldots+k_{i-1}+j} \geqslant 0, \tag{3.8}$$

$$j = 1, 2, \ldots, k_i; \quad i = 1, 2, \ldots, n, \quad k_0 = 0$$

$$u_k \geqslant 0, \; k = 1, 2, \ldots, m_1 + m_2 + N.$$

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According to the second duality theorem, if the solution (3.1) is an optimal solution, then the components u_k^* of the solution of the dual problem with $k>m_1+m_2$ will be equal to zero (since are satisfied the conditions (2.1) with absolute inequality), all limitations (3.8) are converted into equalities (since $x_{ij} \neq 0$), the linear form (3.6) becomes zero (since $\epsilon=0$), and the inequality (3.7) can be written in the form of the equality

$$\sum_{k=1}^{m_1+m_2} u_k^* = 1 + \delta, \quad \text{where} \quad \delta \geqslant 0.$$

Thus, if the solution (3.1) is optimal, then the system

$$\sum_{k=1}^{m_1+m_2} u_k^* = 1 + \delta,$$

$$-\sum_{k=1}^{m_1} u_k^* + \sum_{k=m_1+1}^{m_1+m_2} u_k^* = 0,$$

$$\sum_{r=1}^{m_1+m_2} C_{ij}^{(r)} u_r^* = 0, \quad i = 1, 2, \ldots, n, \quad j = 1, 2, \ldots, k_i \tag{3.9}$$

has a non-negative solution.

Let us denote by R, R_2 and R_1, respectively, the ranks of a matrix M of the system (3.9), its augmented matrix and matrix M_1, which is obtained from matrix M by discarding first line.

Matrix M of the system (3.9) has the following properties:

1) its first line consists of m_1+n_2 ones;
2) the second line has m_1 elements equal to - 1, and m_2 elements equal to 1;
3) the remaining N rows of matrix M can be decomposed into n layers; a layer with number i contains k_i lines; $i=1, 2, ..., n$. In each column of a layer is located one and only one nonzero element equal to - 1, if the column is located in the first m_1 columns, or to +1 for the remaining columns.

Matrix M coincides with the transposed augmented matrix of limits (2.4). Let us note that matrix M has no more than N+2-n linearly independent lines, since the sum of the elements of the columns of each zone is equal to the second row of matrix M. Therefore $R \leq \min(N+2-n;\ m_1+m_2)$. The rank of the augmented matrix $R_2=R_1+1$, since the free terms have only one element different from zero.

Let us call the teaching sequence short if $m_1+m_2<N+2-n$ and long if otherwise.

From all of the aforesaid the following can be stated.

The problem o dividing objects into two classes with one hyperplane will be solved if one of two conditions has been fulfilled:

a) the system (3.9) is insoluble, i.e., $R_2 \neq R$;
b) $R_2=R$, but any solution of system (3.9) has at least one negative component.

For the short teaching sequence the problem of division, in particular, will be soluble if $R_1=m_1+m_2$, since in this case $R=R_1$, while $R_2=R_1+1$, and system (3.9) will be inconsistent. When $R_1<m_1+m_2$ and $R=R_1+1$, the problem of division is soluble if there are different signs for the cofactors of a line consisting entirely of ones of a nonzero determinant of order R (in this case the solution of system (3.9) will have negative components).

The problem of linear programming examined is characterized by great dimensionality ($N+1$ unknowns, m_1+m_2+N limits) and by the comparatively simple structure of the matrix of limits.

Each row of the matrix of limits (2.3) and (2.3') containing n nonzero elements can be written in computer memory in the form of numbers of columns j_{ir} in which are these elements are located.

For solution of this problem it is advisable to use methods which do not revise the initial matrix of limits. This condition is satisfied, for example, by the method of Pietszykowski [6]. As the initial approximation it is useful to adopt the solution (3.1).

Those gradations of parameters which did not belong to the teaching sequence will preserve in the solution values equal to 0.5. Since in the teaching sequence there is no information about the fact that such gradations of parameters are encountered more frequently in one of the classes than in other, then there are no bases for coding them by other numbers.

The value of the code x_{ij} will be more than 0.5 when this gradation of the parameter more frequently is encountered in class A and less than 0.5 if it is characteristic of class B.

4. Recognition objects. As a result of solution of the problem formulated in p. 2 with max $\epsilon>0$ we obtain the table of codes $\{x_{ij}\}$.

For the classification of a certain object it is necessary to determine n values characterizing its parameters and to find for each gradation the code corresponding to it. Let us obtain n numbers. If the sum of these numbers proves to be more than n/2, then the object belongs to class A; if is less than n/2, then to class B. The object is not identified when there is a coincidence of the sum of the codes with n/2.

The method described above was applied in the computer center of the University of Perm to compile recognition tables for dividing beds into the oil-bearing and water-bearing according to the data of geophysical measurements in the Perm region. In one of the problems, in order to characterize a bed, 13 parameters were measured; these included the time of opening a well, thickness of bed, diameter of well, apparent resistance measured by probes of different lengths, etc. Each parameter had from 2 to 6 gradations. In this problem n=13, and the total number of gradations N=54. For teaching purposes we presented on 30 oil-bearing and aquifers, $m_1=m_2=30$. Thus, this problem was reduced to definition of 55 unknowns with 60 limits of type (2.3), (2.3') and 54 limits of type (2.1). In the teaching sequence two gradations of the parameters were encountered only in class A and 3 gradations only in class B, while one gradation was not encountered in any of the objects. The remaining gradations (48 gradations) were encountered in both classes. As a result of the solution a recognition table was obtained; this was used for recognizing beds with no role in teaching.

It is extremely important here to have simplicity of recognition. The interpretation of geophysical measurements in a well can be done with the help of the obtained tables directly at the site of measurements and does not require a highly skilled person.

5. Observations about other methods of optimization. There other criteria of optimality possible. For example, it is possible to maximize the total distance from the dividing hyperplane to all points of the teaching sequence. In this case the linear form with $m_1=m_2=m$ is

$$z=\sum_{r=1}^{2m}\sum_{i=1}^{n}\sum_{j=1}^{k_i} C_{ij}^{(r)} x_{ij}$$

with the limits

$$-\sum_{i=1}^{n}\sum_{j=1}^{k_i} C_{ij}^{(r)} x_{ij} \leqslant \delta_r \frac{n}{2}, \quad r=1,2,\ldots,2m.$$

$$0 \leqslant x_{ij} \leqslant 1.$$

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In the solution of this problem it is possible to have cases where some objects of the teaching sequence prove to be on the dividing hyperplane, and the teaching sequence will be divided incompletely with max z>0.

If necessary it is possible to superimpose on codes x_{ij} some further limits with the form

$$x_{ij}=f_i(j, t_1, t_2, ..., t_s) \qquad (5.1)$$

where f_i - preset linear function of parameters $t_1, t_2, ..., t_s$.

The value of the code x_{ij} will be determined if the parameters $t_1, t_2, ..., t_s$ are found.

The problem in p. 2 will preserve linearity with substitution of relation (5.1) in the limits (2.1), (2.3), (2.3'), but if $s<N$, then the quantity of variables sought is reduced, and max ϵ can only decrease; also narrowed somewhat will be the class of sets divided by one plane.

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